DEVELOPMENT OF WATER PURIFICATION SYSTEM BY MAGNETIC SEPARATION TECHNIQUE AND ITS APPLICATION TO THE EDUCATION FOR ENVIRONMENT ON THE COURSE OF LEARN-BY-DOING PROGRAM

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Abstract:

A superconducting permanent magnet system capable of generating strong magnetic fields has been constructed by using bulk high temperatures superconductors HTS. The magnetic field in the open space between the face-to-face settled magnetic poles has exceeded 3 T when they were activated at 30 K. We have investigated the magnetic separation technique with respect to Fe ions in the waste water drained from the university laboratories. The performances of bulk magnet system closely came to those of 5 T superconducting solenoid with a ratio over 90 % under the flowing rate of 3 liter/min in spite of the narrower space of strong field. The result attributes to the fact that the bulk magnet system has the steepest gradient among them. This suggests that the magnetic separation by using bulk magnets is effective for the practical water purification systems.

The students of Niigata University take various parts in the actual R&D processes that were incorporated as a course of their educational curricula. It is important for the university students to learn the environmental issues by resolving the practical problems surrounding them. In the study, the water purification system has been adapted to the education course to carry out as a project-based learning. We expect that students would acquire strong motivation to learn sciences through the course.

Keywords; water purification, magnet separation, superconductor, practical education

Introduction

The environmental issues have gradually changed the pollution standards toward less value than those of the past in concentration of heavy metallic ions, arsenic, boron, BOD/COD and so on for the surrounding water. For instances, an importance of water purification by separating toxic heavy metallic ions from the waste water which is drained from the university laboratories has been also referred. Since a large amount of additives containing Fe compounds have been used to throw them away, the reduction of additives in the process is needed to reduce the treatment cost. Since the waste water is ordinary purified through various processes in the vast water pools or tanks, it is necessary for us to develop more compact and easier way than usual.

As follows in equation (1), the magnetic force F_m applied to the magnetic particles is given by the product of three elements such as volume of particles, susceptibility and applied magnetic field. We note that the presence of steep gradient is necessary to obtain high magnetic force in addition to the field strength [1].

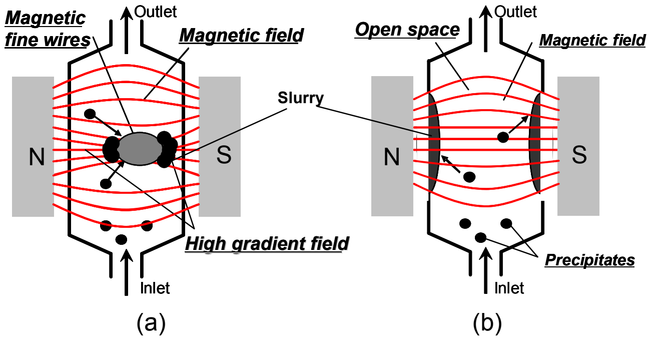


Fig. 1. A couple of types of magnetic separation techniques, (a) high gradient (HGMS) and (b) open gradient magnetic separations (OGMS).

$$\boldsymbol{F}_{\boldsymbol{m}} = \frac{4}{3}\mu_0 \pi r_p{}^3 \frac{9(\chi_p - \chi_f)}{(3+\chi_p)(3+\chi_f)} H \cdot \mathrm{grad}H \tag{1}$$

As shown in Fig. 1, a couple of magnetic separation systems, high gradient (HGMS) and open gradient (OGMS) magnetic separations, have been precisely studied by Okada et al. [2] and Fukui et al. [3]. When ferromagnetic filaments are inserted in the field, the distribution of flux lines between the magnetic poles is changed as to be attracted to the filaments and resultantly high gradient magnetic field yields around the lines (Fig. 1a). On the other hand, we know that the magnetic field generated between the poles originally possesses a wide space with steep gradient (Fig. 1b). The later is ordinarily used in magnetic separation techniques called as the open gradient magnetic separation.

It is known that the melt-processed $REBa_2Cu_3O_y$ (RE123; Rare Earth = Y, Sm, Gd) high temperature superconductors HTS act as permanent magnets when they capture the magnetic fields [4, 5]. The field trapping ability of what we call bulk magnets has been substantially improved by reinforcing the sample to prevent against the fracture that happens due to the magnetic force when they trap the intense magnetic flux density of over several T [6]. The trapped field measured in the open space between two magnetic poles that are settled face-to-face has exceeded 3 T when they were activated by the pulsed field magnetization method operated at 30 K by adopting the Gifford-McMahon (GM) refrigerators. On the other, various kinds of the superconducting permanent magnets using bulk superconductors have been constructed in order to develop the practical and industrial applications [7].

In the paper, we report on the performances of separation ratios of Fe from a view of comparison among the strong field generators such as a superconducting bulk magnet system containing the high temperature bulk superconductors, a superconducting solenoid magnet and a conventional electromagnet. In the activity, the undergraduate students of Niigata University take various parts in the actual engineering research and development processes that are going to be incorporated as a course of their educational curriculum. This practical project is also called as a learn-by-doing education in which the students learn the realization processes, which were actually driven by the undergraduate university students from the initial to senior grades, professors, and researchers of private companies or officials outside the university.

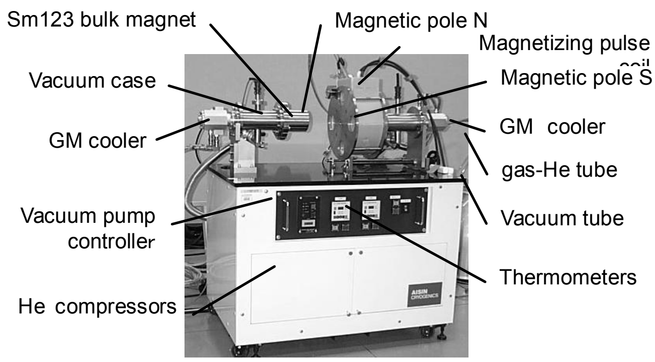


Fig. 2 Face-to-face magnetic generator using a pair of superconducting bulk magnets.

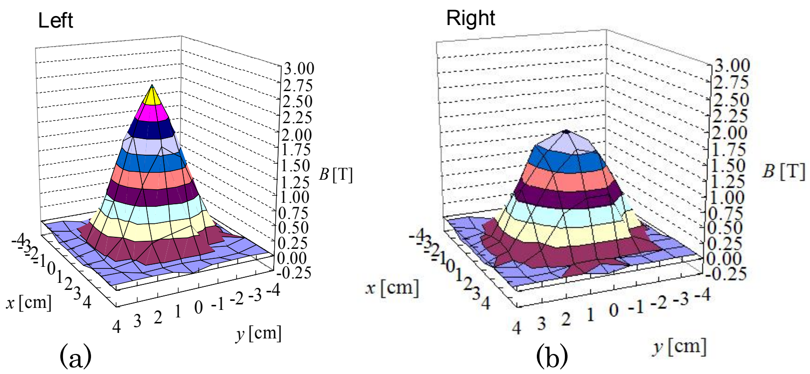


Fig. 3 Flux distribution on the magnetic pole surface for face-to-face magnetic field generator.

Experimental

Figure 2 shows a face-to-face type superconducting magnet system, which consists of a pair of Sm-Ba-Cu-O bulk samples mounted on the respective cold stages of the GM refrigerators in each vacuum vessel [8]. The bulk samples were cooled to 30 K and then magnetized by feeding currents using the magnetizing pulse coils. The rise time of the magnetic pulses was 10 ms. After the activation by the pulsed field magnetization process, the trapped field distribution was measured by scanning a Hall sensor (F. W. Bell BHA921) on the surface of each pole with a gap 0.3 mm.

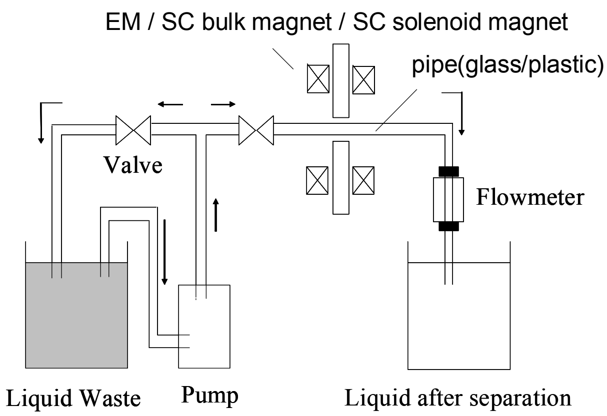


Fig. 4 A view of magnetic separation setup.

The trapped fields measured on the respective surfaces of the chambers are shown in Fig. 3. The maximum magnetic field has reached 2.78 T at the center of the surface of left pole. The profile of magnetic field distribution shows a cone-shape and the maximum magnetic field is located at the centre of the each pole surface. This is an important characteristic of the trapped field of bulk superconductors. The performance of magnetic property has already exceeded the maximum values of the conventional permanent magnets such as Nd-Fe-B and even that of the large scale electromagnets. The authors think that a steep gradient of generating flux distribution is applicable to the magnetic separation technique as follows.

The experimental setup of the magnetic separation is schematically shown in Fig. 4, where SC and EM mean “superconducting” and “electromagnet”, respectively. The waste water including 91.6 ppm of Fe was circulated. A part of the water was led to the glass channel with a diameter of 18 mm settled between the pole pieces of the electromagnet and superconducting bulk magnet generating 1 T and 2 T at the surface of each magnetic pole, respectively. In the operation using superconducting solenoid magnet, the channel was settled through the bore of magnet with a size of 100 mm in diameter, and the magnetic flux density of 5 T was applied to it. The stainless steel mesh with a diameter of 0.1 mm was inserted into the channel with a volume density of 8.1 % for the HGMS, whereas the channel was settled without any filters in it for the OGMS. The water after the treatment was precisely examined for the concentration of Fe by ICP analysis.

Results and discussions

The specifications of three magnetic field generators adapted to the study are shown in Fig. 5. The HTS bulk magnets are characterized as compact and strong magnets with steep gradient, whereas the superconducting solenoid magnets are featured as field generators with vast spaces and uniform fields.

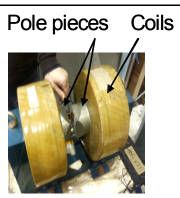
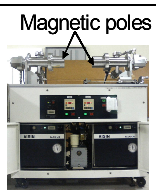
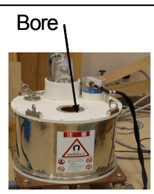
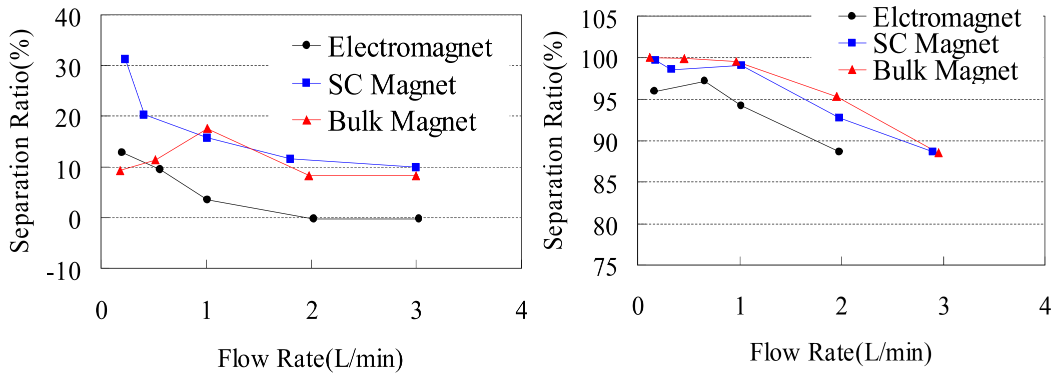
Adopted magnets	Electromagnet	HTS bulk magnet	Superconducting solenoid magnet
			
Magnetic fields	1 T	2.7 - 3.5 T (between the bulk surfaces)	2.5 - 5.0 T (in the RT bore)
Space of field	50x50x20 mm3	fai 65x20 mm3	**fai 100x440 mm3**
Power consumption	1,030W	1,300W	6,500W
Field gradient	14.7 T/m	**113.8 T/m**	43.5 T/m
Weight		190 kg	300 kg

Fig. 5 A list of magnetic field generators examined in the study.

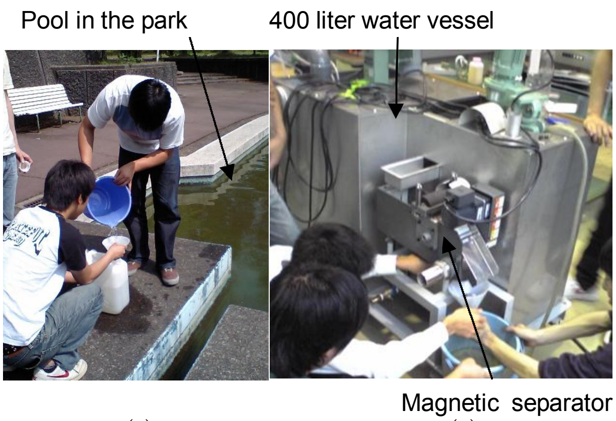


(a) (b)

Fig. 6 Separation ratios of Fe against flowing rates for (a) open gradient OGMS and (b) high gradient magnetic separation HGMS.

Figure 6 shows the separation ratios of Fe precipitates against the flow rates of slurry water. The data were obtained by using the system shown in Fig. 5 in the case of HGMS (Fig. 6a) and OGMS (Fig. 6b), respectively. In both figures, it is easy to understand that the separation ratios of HGMS exhibit the data more than 90 % whereas that of OGMS showing less than 30 %, which decrease with increasing flowing rate up to 3 liter/min, and the data of bulk magnet and SC magnet occupy the superior region to that of electromagnet. It must be, however, noted that the lines come close to each other without showing any substantial differences between them especially on the region where the flow rates exceed 1 liter/min. This implies that the steeper magnetic field gradient yielding around the bulk magnet attributes to this phenomena in spite of the narrower space than that of SC magnet. Furthermore, the precise measurements are necessary to clarify the fact in near future.

We have started a practical learn-by-doing program conducted by the collaboration among the university students, professors, and engineers of companies. The investigation is carried out by adopting the first to forth grade undergraduate students of Niigata University, as shown in Fig. 7. The students gather the sample waters (Fig. 7a) and magnetic separation experiment is attempted after the cohesion treatment by the water purification system, as shown in Fig. 7b. The concentration of remnant substances such as Fe in the underground water is estimated by using the conventional magnetic separator with permanent magnets, for instance, with respect to the separation ratios against the various flowing rates of the water.



(a) (b)

Fig. 7 water purification project using con ventional permanent magnet separator

The estimation on the students is to be given by examining their reports on the experiments and the presentation skills during and after the course.

The project is based on the extremely peculiar technique using HTS, which requires them to have well-advanced scientific knowledge and experiences that university students would acquire with respect to every fundamental abilities of engineering technologies. This education program is on its way of a trial, and we believe that practical and industrial demands give students substantial motivation and responsibility through the realization processes driven by engineering techniques.

Conclusions

The water purification experiment has been conducted by university undergraduate students with respect to the Fe ions involved in the waste water by using HTS bulk magnet system which yields strong magnetic field over 3 T. The Fe precipitates of the waste water drained from the laboratories were effectively removed with a trapping efficiency over 90 % for HGMS and 9% for OGMS experiment under the region of flow rates up to 3 liter/min. The performances of HTS bulk magnet and SC solenoid magnet approximately equal to each other in spite of the size of exposure space and time of flowing water. This attributes to the steep magnetic gradient of bulk magnet system, which apparently shows an advantage to other methods. The novel education program is to be started aiming an enhancement of the motivation and responsibility on the job through the practical and actual development process driven by the engineers outside university.

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